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An Approach for the Sensory Integration into the Automated Production of Carbon Fiber Reinforced Plastics

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Abstract

The advantages of Carbon fiber reinforced composites (CFRC) lead to an increasing demand of Carbon fiber products. This class of materials is gaining widespread acceptance in various fields like aviation, wind energy or automotive and is gradually replacing traditional lightweight construction materials such as high-strength steel or aluminum. Currently, particular process steps of the production of fiber composite structures are performed manually or semi-automatically. Especially the automated handling of semi-finished products consisting unstable textile poses a challenge for an economical manufacturing. The reasons for the missing automation are beside the lacking technical feasibility most of all, reliability issues during process execution, representing key aspects for potential large-scale production. As a consequence, the integration of sensor systems constitutes a promising approach for process optimization and quality assurance. In order to catch the intricate nature of possible defects and their interdependences during the single steps of the handling process, an approach for selecting, assembling and integrating the ideal sensors at the respective processing station to monitor dominant defects is presented. For this purpose, possible defects and flaws are derived from a comprehensive process analysis and accordingly suitable sensor principles are selected. The application of this approach is exemplarily demonstrated on an automotive case study focusing the separating and draping steps of flat carbon fiber textiles in a mold for a resin transfer molding (RTM) process.

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1. Introduction and Motivation

Current discussions on energy and resource efficiency have significantly influenced the importance of fiber reinforced plastics (FRP). In addition, present social trends such as sustainability and environmental awareness place FRP in the focus. The rising desire for low-emission mobility in the future, emerge in novel challenges in the areas of electrification and lightweight. Thereby, FRP components possess a high potential for the implementation of lightweight structures [1]. Especially its construction and the anisotropic structure provide technical advantages over existing materials in production technology.

Novel approaches in the design and the operation of technical systems can be realized in various industries, such as the aerospace industry and the automotive industry [2,3]. Nevertheless, the structural and mechanical advantages are facing high material and manufacturing costs inhibiting further dissemination and full market penetration. The detailed cost structure of a CFRP (carbon fiber reinforced plastic) component which is manufactured by a conventional RTM process is depicted in Fig. 1.

The total manufacturing costs along the value chain cause a proportion of 64 %. This suggests that especially the reduction of this cost share represent an important lever for mitigating the major industrialization burden.

In order to enable a sustainable and economic production; the following requirements have to be considered:

- Increasing the level of automation in manufacturing by reducing manual operations

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- Enhancing process reliability by stable operations to reduce downtimes
- Reduction of throughput time by lowering cycle times for individual processing steps
- Lowering rejection rates by appropriate quality assurance approaches

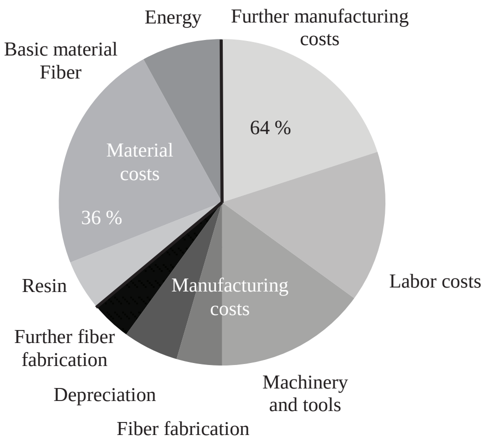

Fig. 1. Composition of the costs of a CFRP component [4][1]

Due to the high cost reduction potential, this paper is focused on the handling steps, which are required to connect the decoupled process steps. Exemplary for the preforming, the handling of instable form and contour variant CF-textiles are considered. These textiles have to be deposited in the mold layer by layer according to the required fiber orientation. Resulting from the anisotropic structure of the textiles a slight difference of the fiber orientation causes a debilitation and significant decrease of the stability characteristic (e.g. 35 % diminution of strength resulting from fiber deviation of 5 °). For example, conventional components in the aviation industry consists of up to 15 layers which have to be placed independently with high attention to their positions in order to enable further processing of the preform.

To ensure high availability for the entire preform process, high robustness must be ascertained for the individual handling steps. Based on the objectives, the automated and reliable handling using appropriate quality assurance measures can be derived as a target. The technical feasibility of the implementation of an automated process has been successfully demonstrated [5,6]. In manufacturing processes, there exist various options to ensure the quality, such as the subsequent listed [7]:

- Away from production – sampling inspection apart from production
- Related to Production – sampling inspection right next to the production
- Integrated in machinery – plant-integrated system for measuring during off-peak hours
- Inline – integrated inspection as a separate additional step in the process chain
- Parallel to manufacturing (online) – integrated inspection during the value-added step with a potential control system in the process

With reference to the described demands the focus is subsequently placed on the online quality assurance as the most appropriate solution. Especially for a handling operation the required partial steps, wherein errors occur during the operation, are identified and provided with suitable sensors following a comprehensive process analysis. The objective is to develop a process-synchronous quality monitoring and control technology of given error sources. Further potential weaknesses have to be identified in order to detect rework at an early process stage. An additional objective is placed on the development of process knowledge for the complex handling operations, wherewith the potential for cost reduction can be reached for further process steps.

2. State of the Art

In literature numerous approaches to quality assurance, as are illustrated in Fig. 2, can be found along the production chain. The classification is orientated towards an industrial process chain for the production of CFRP structures using the example of the RTM process.

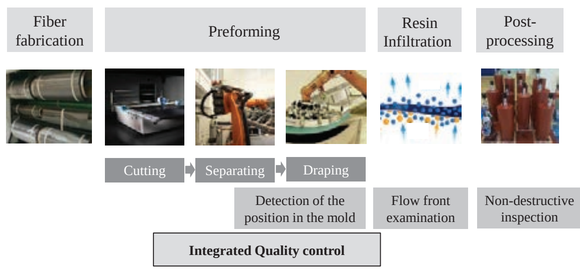

Fig. 2. State of the art of the CFRP production

Generally, the inspections of the finished components are executed with destructive and non-destructive methods as a final step. The most common non-destructive approaches use ultrasonic or thermographic testing methods. Two further methods such as radiography and eddy current testing are also widespread, whereas other possibilities result by using magnetic sensors [8]. Using non-destructive approaches errors such as delamination's, cracking, disbonds, voids, porosity, inclusions and fiber defects can be detected [9]. A decision support for selecting an appropriate testing method is given by [10]. Additional non-destructive tests with finished components are investigated by [11,12,13,14,15]. The inspection is also realized for special applications such as, complex structures [16], joints [17,18] or metallic hybrid constructions [19].

The aforementioned process step deals with the resin infiltration into the current dry textile construction. The flow fronts of the resin as well as the distribution of the matrix

[1] Dimensions 0,8 m x 0,8 m, weight 1,8 kg, complete component costs 50 €-60 €

material influence the strength and the properties of the final component. For checking the infiltration in the resin injection approaches such as the capacitive measurement technology are tested [20].

The earlier the inspection can take place and errors can be detected, the higher is the cost reduction potential. For this reason, the dry fiber structure is checked for errors with resin prior to infiltration. Reference [21] inspects the dry fiber construction in view of possible errors with the approaches of non-destructive testing. An alternative approach checks the position of the textiles after the laying process step using vision [22] or laser sensors [23].

Due to the specified increase of the reject costs along the fabrication process and the determination of the fiber orientation at the handling process, there exists the demand to perform the quality assurance – as an early process step – during the handling process. With respect to the requirements for economic production and the quality targets, currently there are no solutions for a continuous error examination during the handling process.

3. Objective and paper structure

The objective of the presented paper is deduced from the proposed motivation and the presented state of the art and research. Based on the reference process of the handling of unstable CF Textiles a systematic deductive approach is presented for a structured process analysis with the aim of the sensor selection and integration. First, the methodology is introduced and illustrated. Subsequently, the required sub-steps are described in detail to specify the exact procedure. Using the mentioned reference scenario the methodology is finally applied and evaluated.

4. Methodology

4.1. Overview

The developed process model is visualized in Fig. 3. The procedure is divided into four levels, which has to be traversed to solve the problem successively [24, 25]. These are the

- Request level,
- Functional level,
- Feasibility level and the
- Manufacturing level.

By using different levels, the problem is executed from an abstract process description to a definite problem specification. According to receiving and processing requirements, the individual weaknesses in the system are derived. Subsequently, independent solutions are designed for all failure points. The focus is placed on the CFRP production, that is why special suitable sensors are used which are qualified for this application in numerous experiences. Then, the solution concepts are described in detail in the manufacturing level and are qualified for the application. The individual and independent quality assurance concepts are merged resulting in a detailed overall concept for implementation. Key issue of the methodology is the general applicability for other issues. The input data of the scenario which are processed in the feasibility level und the manufacturing level define the use case.

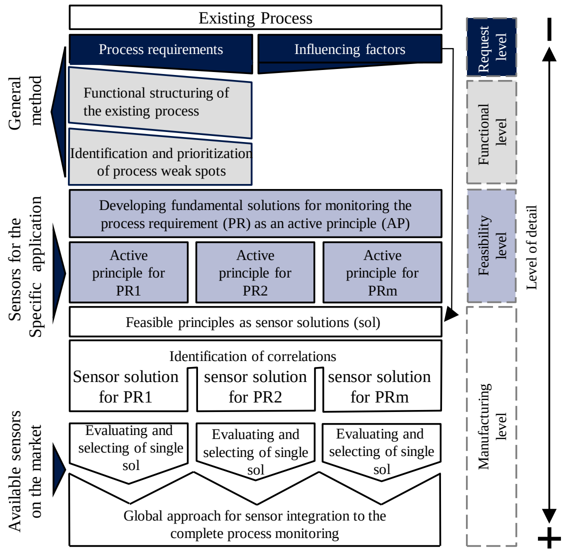

Fig. 3. Overview of the methodology

4.2. Detailing

4.2.1. Request level

Starting with a requirements analysis process demands and variables are added to the description and structuralizing of the considered process. The requirements are numbered, prioritized and supplemented with formalized values, tolerances and dimensions. A specific list of requirements already restricts the solution space. The process requirements (PR) can be classified into four categories:

a) Functionality,
b) Performance,
c) Quality and
d) Profitability

Using the example of a handling process, there are laying tolerances of textiles, required cycle times or system availability. All urgencies are compared in pairs in a target preference matrix to identify the hierarchy of formulated process requirements. In contrast, influencing factors cause an effect on a system or to a single feature of the system. Using an Ishikawa diagram influencing factors are illustrated allowing a transparent representation of the causal relationship between causes and effects. It is divided into material-specific, process-specific and product-specific factors of influence. For example, there is the characterization of textile semi-finished products as well as partial steps used during handling. Finally, the connection matrix establishes the connections between the considered process requirements and the influencing factors.

4.2.2. Functional level

The functional level considers the interaction of a system with its surroundings within the defined system boundaries (e.g. specification of the status of the textiles prior to the handling operation). The space for the solution supports to restrict defined system boundaries. The next step is to develop a relation-oriented functional model for the identification and characterization of vulnerabilities. Initially, the process is subdivided in its elementary sub-steps. Thereof potential weaknesses can be identified, which are rated into harmful functions. Having a comparison of the harmful functions with the process requirements, the elementary weaknesses are formulated and used as input for the next level.

4.2.3. Feasibility level

The objective of the feasibility level is to generate initial solutions for the continuous sensor integration. At this point, application-specific information is necessary for the methodology, which can be introduced by expert knowledge. Thus, the approach is substantiated by the required input. In the present case, with a selection of possible sensor principles which are suitable for textiles semi-independent partial solutions to the harmful functions are developed. Here, the present (PR)s and influencing factors of the corresponding harmful functions are considered. Thus for all these harmful functions there are fundamental solution modules based on the active principles (AP).

4.2.4. Manufacturing level

In the Manufacturing level the merging and itemization of the generated solution modules from the operative level is accomplished to a final overall concept. Specifically, a sensor arrangement for the complete handling process at the physical level is developed in terms of a description with criteria, such as:

- Task description with the prioritized purpose of the solution: Due to the different sensor principles each sensor performs the task in a variable way
- Sketch of the assembly of the sensor
- Module as a recommendation of the location of the assembly
- Influencing factors (with value and dimension)
- Geometric Description
- Process environment (protection class of the sensors, additional required equipment)
- Guidelines for the assembling

Subsequently, the singular sensor solutions are summarized to potential overall concepts by combining different sensors to feasible paths. In order to evaluate a suitable overall solution, a morphological analysis of all PRs is carried out which includes the presented partial solutions of the foregoing steps and performs a choice and evaluation of selection criteria for every path. A selection of the essential criteria with examples is listed below:

- Costs (investment and operating costs)
- Connectivity (geometric connection, installability, software)
- Operating behavior (reliability, redundancy)

The prioritization of the criteria depends on the focused business. Table 1 distinguishes the relevant sectors for application of CFRP, divided into commercial industry and private sector.

Table 1. Different target sectors for the application of CFRP

	Aerospace	Automotive	Mechanical Engineering	Other Business
Commercial	**X**	**X**	X	X
Private		X		X

Depending on the business, a different weighting and prioritization of the criteria is performed. For example, in the commercial sector for the automotive industry, the costs are prioritized to the operating behavior. In contrast, reliability and redundancy have the most priority in the aerospace industry. Finally, with a discrete scoring (0/1/2)[2] for the choice of not/partly/complete feasible) the final decision of the overall concept is executed.

In summary, the methodology offers a definite approach for fault detection and derivation of process weaknesses for handling processes.

5. Use Case

5.1. Introduction and presentation

The methodology is exemplarily illustrated using an automotive case study focusing on a production process of CFRP components. The focus is set to low unit costs while reducing the cycle time [26]. The observed sub process addresses the handling of instable textiles after the cutting process up to the preforming in the mold. The result is a dry preform which is infiltrated with resin in the subsequent process step. Fig. 4 depicts the process.

After the cutting process the semi-finished textile products are picked up from the cutter table with a separating tool [27,28].

Then they are stored on a tacking table. In the following step, the single layers are lifted with a preforming tool and draped in a mold. For form instable textiles the handling of the textiles is based on the low vacuum principle which has proven to be a suitable approach [5]. Subsequently, the

[2] The choice of 0 is an knock-out-criterion and disqualifies the considered path.

preforming process will be analyzed with regard to its process stability and to the observance of quality requirements.

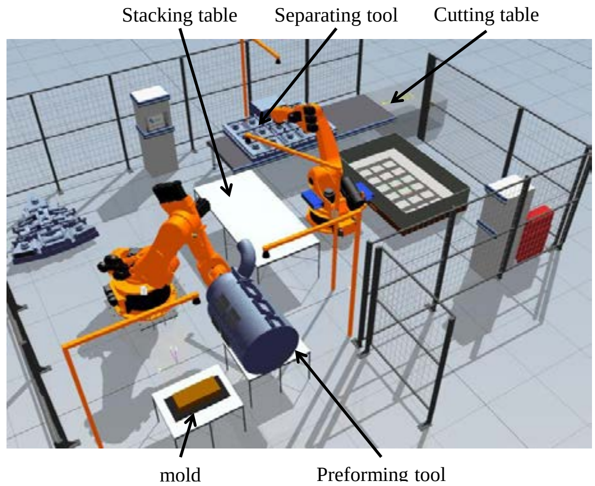

Fig. 4. Visualization of the Case Study

5.2. Implementation of the methodology

In the following, the approach is proposed to increase the process reliability and the quality during the handling of the reference scenario. Here, the presented methodology is applied. Fig. 5 shows the connection matrix as the result of the request level.

Factors of influence			Process requirements: Functionality				Process requirements: Performance				Process requirements: Quality	
			Precise, shape supporting gripping	Precise, shape supporting draping	Reliable clamping	…	Short cycle time	Small batch sizes	Reproducibility	…	Positioning in the mold	…
Material-specific	Fiber	Bending stiffness	3	3	3						1	
		Type of fiber	3	3	3							
		Diameter of the fiber	1	1	1						1	
		…										
	Array	chemical resistance										
		permeability					3	1	1			
		melting viscosity					9				1	
		…										
	Semi-finished textile	Dimensions	9	9	9						9	
		Fiber orientation		1							3	
		Basis weight	3	3	3							
		…										
…												
Product-specific	Quality	Design element										
		Tolerances of position	3	9	3				9		9	
		Surface quality							3		3	
	Organi-sation	Piece number					3	3				
		Variants	3	3	3		3	3	3			
		Product life cycle							1			
	Load	Costs of components					1		1			
		Application of force										
		Stability										
…												
Process-specific												

Fig. 5. Connection matrix with factors of influence and process requirements

Thereby a small sample of the most important requirements is displayed in comparison to the influencing factors. In the category functionality the requirement PR 1, "precise, shape supported gripping" occurs as the most important requirement in the correlation matrix. Based on the defined characteristics of the influencing factors the areas are detailed with the result that all major variables are included and declared. The linking between the two variables is performed with respect to their interference. Starting from "Blank" (no impact) to "1", "3" and "9" (high control) the level of interference is described. The evaluation is carried out by an expert survey (n=?).

The results of subsequent levels are summarized in Fig. 6. The harmful functions are derived in the functional level. For the depicted requirements five functions can be identified, which handle with the precise positioning and safe gripping aspects. From the AR specific sensors are stored in the building plane, which illustrates partial achievable solutions for the harmful functions. With this recommendation, the desired specifications of the sensors and the influencing factors an overall solution is derived, wherewith an assurance of the quality can be guaranteed for all weakened spots at the corresponding position. This ensures that only solutions are developed for those harmful functions which represent potential weak spots. The process is finally equipped with two sensor systems, which are described below:

Requirements	**PR1**, precise, shape supported gripping	**PR2**, reliable clamping				**PR4**, positioning accurancy
Modules	Stacking table	Preforming Tool				Mold
harmful functions / **sensor**	Missing positioning and orientating	Insufficient gripping	Falling down of the textile	Textile out of tolerance range	…	Incorrect position in the mold
Laser distance sensor	X	X	X			
CCD line sensor	X					X
CCD sensor camera	X			X		X
CCD array sensor camera	X			X		X
CMOS camera	X			X		X
…						
Capacitive proximity sensor		X	X			

Fig. 6. Singular sensor solutions

- Capacitive sensor:
  The sensor is integrated into the surface of the handling system and detects the dropping down of the textiles. The inspection of the presence is carried out along the entire duration of the handling.
- Vision system:
  After picking up the textile by the gripper the handling system moves over the camera range. Afterwards, an image position of the textile is recorded and analyzed. Then the textile position is returned to the robot control within the feedback control providing deviation information. If necessary, the robot control compensates the detected displacement and ensures a correct drop into the mold.

6. Conclusion and outlook

The high costs in the production of composite structures arise largely due to the high share of manual handling operations. In addition to the lack of process safety, one main reason is the high rejection rate as a result of missing testing routines of semi-finished products during the manufacturing process. Online quality assurance offers the possibility to map a stable process without further process steps and higher cycle times using appropriate sensors. In this paper using the example of handling processes suitable sensor solutions were identified.

Thereby, a methodology for the sensory integration into the automated production of carbon fiber reinforced plastics has been developed. In this case, after analyzing the requirements and the types of errors as well as considering the available sensors, the existing handling process was extended by integrating a capacitive proximity sensor and a vision system.

In a subsequent paper the implementation of the sensor systems into an existing handling process as well as the experimental validation will be presented and discussed. It is expected to realize a cost-effective solution under discovery and prevention of the most prevalent disorders. As a final step, an economic evaluation with regard to the expected benefits of the system can be carried out highlighting the potential impact.

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References

[1] M. Neitzel, P. Mitschang, and U. Breuer, Manual composites, materials, processing, application, Carl Hanser, Munich, 2014.
[2] H. Schürmann, Designing with fiber-plastic composites, Springer, Berlin, 2005.
[3] R. Heuss, Lightweight, heavy impact; How carbon fiber and other lightweight materials will develop across industries and specifically in automotive; Advanced Industries; McKinsey & Company, 2012.
[4] Acmite Market Intelligence; Global Carbon Fiber Composite Market, Watwill, Switzerland, 2014.
[5] G. Reinhart, G. Straßer, “Flexible gripping technology for the automated handling of limp technical textiles in composites industry”. Production Engineering 5, pp. 301-306, 2011.
[6] G. Reinhart, C Ehinger, “Robot-based automation system for the flexible preforming of single-layer cut-outs in composite industry”, German Academic Society for Production Engineering WGP, Heidelberg, 2014.
[7] R. Schmitt, B. Damm, “Test and Measurement on cycle”, QZ 9, Carl Hanser, Munich, 2008.
[8] C. Carr, D. Graham, J.C. Macfarlane, G.B. Donaldson, “SQUID-based nondestructive evaluation of carbon fiber reinforced polymer”, IEEE Trans. Appl. Supercond. (IEEE Transactions on Appiled Superconductivity), 2003.
[9] Air Washington, “Quality Assurance and Nondestructive Evaluation of Composite Materials”, 2013.
[10] A. Kochan, “Research on the non-destructive testing of CFRP components for the in-process quality assurance in the automotive industry”, Phd-thesis, Shaker Verlag, Aachen, 2012.
[11] C. Niu, “Composite airframe structures”, Practical design information and data, Conmilit Press, Hong Kong, 2010.
[12] M. Kersemans, W. Van Paepegem, F. Zastavnik, J. Gu, H. Sol, J. Degrieck, “”Nondestructive characterization of the elastic Properties of orthotropic composites with Ultrasound”, Advanced composites, the integrated system, SETEC 11, SAMPE Europe Technical conference and table-top exhibition, pp. 204-211, Leiden, 2011.
[13] S.T. Peters, Handbook of composites, Chapman & Hall, London, 1998.
[14] M. Rheinfurth, G. Busse, “Non – contact ultrasound for single - sided detection of fatigue and defects in composites”, 18th International Conference on Composite Materials, 2012.
[15] C. Carr, D. Graham, J.C. Macfarlane, G.B. Donaldson, “SQUID-based nondestructive evaluation of carbon fiber reinforced polymer”, IEEE Trans. Appl. Supercond. (IEEE Transactions on Appiled Superconductivity), 2003.
[16] K. David, “Nondestructive inspection of composite structures: Methods and practice”, 17th World Conference on Nondestructive Testing, Shanghai, 2008.
[17] E. Maeva, “Ultrasonic Imaging Techniques to Evaluate Quality of Fiber Reinforced Composite Materials and their Adhesive Joints”, 5th Pan American Conference for Nondestructive Testing, Cancun, 2011.
[18] G. Reinhart, C. Ehinger, T. Philipp, J. Schilp, Y. Shen, R. Spillner, C. Thiemann, “Novel automation technologies for an efficient production of fibre reinforced plastics (FRP) structures at a glance”, SETEC 11, SAMPE Europe technical conference and table-top exhibition, Leiden, 2011.
[19] K. Drechsler, research project Forcim3a, CRP and metal hybrid construction on Machinery & Equipment, Augsburg, 2011.
[20] M. Arnold, “Kapazitive Capacitive measuring technology for RTM process monitoring”, Sensortechnik im Werkzeug, Leightweight-design, Wiesbaden, 2013.
[21] G. Lanza, D. Brabant, “Measurement technology for FRP quality assurance; Prevent damage to fiber reinforced plastics using appropriate inline measurement technology”, wt Werkstatttechnik online, Düsseldorf, 2012.
[22] A. Miene, M. Heumüller, F. Weiland, C. Weimer, “Quality Assurance System for aircraft structural Profile Preforms; Advanced composites, the integrated system”, SETEC 11, SAMPE Europe Technical conference and table-top exhibition, pp. 259-266, Leiden, 2011.
[23] T. Ullmann, T. Schmidt, S. Hofmann, R. Jemmali, “In-line Quality Assurance for the Manufacturing of Carbon Fiber Reinforced Aircraft Structures; International Symposium on NDT in Aerospace”, Hamburg, 2010.
[24] U. Lindemann, Methodological development of technical products, Springer, Heidelberg, 2009.
[25] K. Ehrlenspiel, A. Kiewert, U. Lindemann, Cost effective development and construction, Springer, Heidelberg, 2005.
[26] P. Giliard, J. Graf, M. Jelinek, “Efficient production of fiber composite components by Automation”, Internationales Forum Mechatronik, IMS Institut für Mechatronische Systeme, Winterthur, 2013.
[27] J. Graf, P. Stich, “Possibilities and limitations in automated handling processes” “CFK-Handling leicht gemacht – Möglichkeiten und Grenzen bei der automatisierten Handhabung”, Ingenieursspiegel, Bingen, 2014.
[28] G. Reinhart, G. Straßer, C. Ehinger, “Highly flexible automated manufacturing of composite structures consisting of limp carbon fibre textiles”, SAE International Journal of Aerospace, pp. 181–187, 2010.